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Detection of valley currents in graphene nanoribbons

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ABSTRACT

There are two valleys in the band structure of graphene zigzag ribbons, which can be used to construct valleytronic devices. We studied the use of a T junction formed by an armchair ribbon and a zigzag ribbon to detect the valley-dependent currents in a zigzag graphene ribbon. A current flowing in a zigzag ribbon is divided by the T junction into the zigzag and armchair leads and this separation process is valley dependent. By measuring the currents in the two outgoing leads, the valley-dependent currents in the incoming lead can be determined. The method does not require superconducting or magnetic elements as in other approaches and thus will be useful in the development of valleytronic devices.

1. Introduction

The recent high level of interest in two dimensional materials [1,2] is not only due to their special electronic [3,4] and spintronic properties [5–8], but also due to the potential applications in valleytronics [9–11]. In the Brillouin zones of these materials, there are two inequivalent valleys which are related by time-reversal symmetry. Electrons can be in either one of the two valleys and the valley index is an additional degree of freedom which can be used to carry information. The exploitation of the valley degree of freedom instead of the electrical charge in valleytronic devices requires the following functions: generation, control and detection of valley polarized current [12–18]. Various methods have been studied for the generation of valley polarized current, such as quantum pumping and optical excitation. The manipulation of the valley degree of freedom has been studied by Lee et al. [19] and the valley selection rule in a Y shaped graphene zigzag ribbon structure has been investigated by Zhang and Wang [20]. Methods of detection for valley polarization have also been studied, which requires either superconductors or magnetic elements [21–23]. Akmerov and Beenakker [23] studied the Andreev reflection in a bulk graphene-superconductor junction and proposed using the junction conductance to detect the valley polarization of quantum Hall edge states. Wu et al. [22] studied the valley-dependent Goos Haanchan effect in a strained graphene waveguide and proposed the use of a valley filter constructed with strained graphene and a ferromagnetic strip as a detector of the valley polarization. In graphene zigzag nanoribbons [24], there are two valleys, K and K', in the band structure, which resembles the bulk band structure. The current in a zigzag ribbon can thus be valley polarized to carry information. Recently, in an experimental study of graphene electron waveguides [25], where electrons are confined by metal gates, it is found that the electron conduction quantizes in steps of $4e^2/h$, which is a characteristic of zigzag ribbons, although the orientations of these waveguides can be different from the zigzag direction. This indicates the valley characteristics of zigzag ribbons are preserved in metal-gate waveguides along other directions. This study confirms the important role of zigzag ribbons in the development of valleytronic devices and it is therefore important to know how one can detect and measure valley polarization in zigzag ribbons. Nevertheless, this important issue has not been addressed with due attention. We therefore describe in this paper how a T junction, which is formed by joining an armchair ribbon to a zigzag ribbon as shown in Fig. 1, is used to measure the current valley polarization in a zigzag ribbon. Since no superconducting, strain or magnetic elements are used, the method can lead to simpler fabrication procedures and device designs for valleytronic devices and will play an important role in their development.

2. Model

We consider in this study T junctions constructed from an armchair ribbon and a zigzag ribbon as shown schematically in Fig. 1 with the armchair ribbon lying along the x-direction and being perpendicular to the zigzag ribbon, which lies along the y direction. Since the symmetries of the two ribbons are different from the bulk symmetry, the ribbon unit cells should be different from

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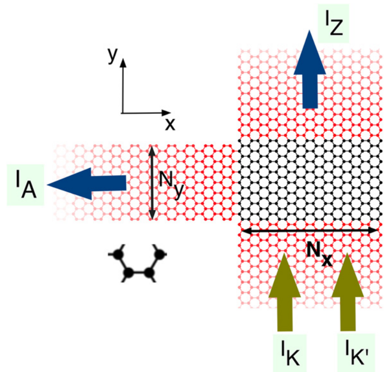

Fig. 1. (Color online.) The schematic diagram of the T junction considered. The arrows show the current flow in the junction when it is used to detect the valley dependent currents I_K and $I_{K'}$. I_A and I_Z denote the outgoing currents in the armchair and zigzag ribbons respectively. The inset shows the 4 atoms in the unit cell structure used to build the junction. N_y is the number of unit cells along the transverse direction of the armchair ribbon and N_x is the number of unit cells along the transverse direction of the zigzag ribbon.

the bulk one. The structures of the two ribbons can be described using a unit cell defined by two vectors, $(3a, 0)$ and $(0, \sqrt{3}a)$, where a is the carbon–carbon bond length. In each unit cell there are four atoms at the positions $(0, \sqrt{3}a/2)$, $(a/2, 0)$, $(3a/2, 0)$, $(2a, a/2)$. The arrangement of these atomic sites are shown in the inset of Fig. 1. The translation vector for the zigzag ribbon is $(0, \sqrt{3}a)$, which is along the y direction. As a result, the ribbon lies along the y direction. For the armchair ribbon, the translation vector is $(3a, 0)$, which is along the x-direction. The width of the zigzag ribbon is denoted by N_x, the number of unit cells along the x-direction in the zigzag ribbon. For the armchair ribbon, the width is denoted by the number of unit cells along the y-direction, N_y. The armchair ribbon constructed with this unit cell does not possess reflection symmetry. To construct an armchair ribbon with mirror symmetry along the longitudinal direction, we need to remove the two atoms at positions $(a/2, 0)$, $(3a/2, 0)$ in the last row unit cell. For example, in Fig. 1, the armchair ribbon is constructed with 8 unit cells along the y direction. Two atoms in the $N_y = 8$ unit cell are removed so that the ribbon and the T junction can both have mirror symmetry. For identical N_x and N_y, the width of the zigzag ribbon is $\sqrt{3}$ times of the width of the armchair ribbon as the x dimension of the unit cell is $\sqrt{3}$ times of the y dimension.

We use the tight-binding Hamiltonian $H = \sum_i e b_i^+ b_i + \sum_{<ij>} t(b_i^+ b_j + b_j^+ b_i)$ to describe electron motion in the junction, where $b_i^+ (b_i)$ denotes the creation (annihilation) operator of site i. The first summation in the Hamiltonian is over all the atomic sites i of the structure considered and the second summation is over neighboring sites with indices i and j. e is the orbital energy of the identical atomic sites and $t = 2.8$ eV is the hopping energy between two sites. In this study, the energy is expressed in unit of t for convenience.

The transmission properties of the junction can be found from the wave functions of the structure, which consist of the incident and the reflected waves, in the incoming lead. In the outgoing leads, the wavefunction depends on the scattering matrix $\tilde{s}$ as in $\sum_m s_{mn}^p \psi_m^p(i) + \sum_r s_{rn}^e \psi_r^e(i)$, where p (e) superscript represents the propagation (evanescent) modes. n represents the incident modes and m represents the outgoing modes. The total conductance at Fermi energy E_F is $G = (e^2/h) \sum_{mn} |s_{mn}(E_F)|^2$, where the summation is over all the outgoing and the incident propagation modes. The valley dependent conductances are obtained by summing only the modes in the corresponding valleys. To find the scattering wave functions and the transmissions, we use the Kwant python package for quantum transport calculation [26]. According to Ref. [26]

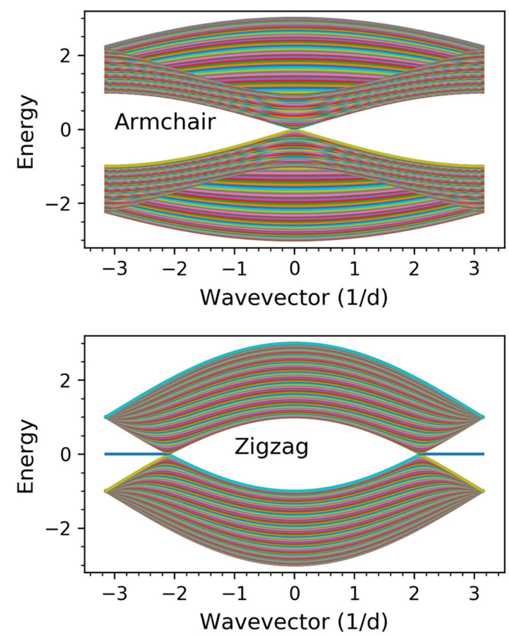

Fig. 2. (Color online.) The subbands of the armchair and zigzag ribbons. d denotes the length of the translational vector of the ribbon. $d = \sqrt{3}a$ for zigzag ribbon. $d = 3a$ for armchair ribbon. Energy is in unit of t, the hopping energy. The numbers of unit cells in the transverse direction are 50.

the wave function in the scattering region and the wave functions in the leads are inserted in the Hamiltonian, which is equivalent to matching the wave functions of the scattering region and the leads. The Hamiltonian equation is then converted into a system of linear equations which also includes the effect of the outgoing and evanescent modes in the leads. The system of linear equations obtained is sparse, which can be solved efficiently by some sparse matrix libraries to find the wave function and the scattering matrix. The use of sparse matrices is the reason why the Kwant package can be faster than the recursive Green's function approach in medium and large systems. The details of the algorithm will be described in details in a forthcoming publication by the Kwant developers.

3. Results

In Fig. 2, the subband structures of an armchair and a zigzag ribbon are shown where two valleys can be identified in a zigzag ribbon and one valley is identified in an armchair ribbon. Similar band structures are obtained by Brey and Fertig [27] using a k.p approach. The numbers of unit cells in the transverse dimension in both ribbons are 50. The two valleys in a zigzag ribbon can have different populations of electrons and carry different currents. The valley polarization of the current in the zigzag ribbon is defined as $P_v = (I_K - I_{K'})/(I_K + I_{K'})$, where $I_{K(K')}$ is the current in the K (K') valley in the incident zigzag ribbon (shown schematically in Fig. 1). Here, the K valley in the zigzag ribbon consists of subbands with wave vector > 0 and the K' valley consists of subbands with wave vector < 0. The valley polarization is a way of representing information and therefore it is necessary to have a method to detect the valley polarization in a graphene nanoribbon. Consider a zigzag graphene nanoribbon with different current flows in the two valleys. If the zigzag ribbon is joined with an armchair ribbon to form a T junction as shown in Fig. 1, the valley-dependent currents in the zigzag ribbon is divided into the two outgoing arms of the junction. By measuring the currents in the outgoing leads, which are denoted by I_A and I_Z, we can deduce the valley polarization of the current in the incoming lead with an approach